Modeling and Control of an Adaptive Tire-Inflation System Based on In-Tire Sensing Feedback

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

THE UNIVERSITY OF TEXAS AT AUSTIN

December 2017

Modeling and Control of an Adaptive Tire-Inflation System Based on In-Tire Sensing Feedback

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The University of Texas at Austin, 2017

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Tire contact area is an important feature that influences the performance of a ground wheeled vehicle, especially on soft terrain. This thesis evaluates a system meant to control tire-surface contact area by inflating and deflating the tire while the vehicle is in motion. The system includes a measurement of the vertical deflection of the tire using ultrasonic distance sensors, from which tire-surface contact area can be inferred from a model basis. In order to validate the concept and determine limits on such a system, a model and simulation of a controlled system has been developed. For the purposes of this study, it is assumed that the tire is operating on a hard (i.e., non-deformable) terrain, the contact area is elliptical, and the tire deflection can be predicted by a 1-D stiffness model. The system was evaluated using three driving scenarios, namely a change in terrain stiffness, changes in vertical applied load, and pressure changes in the tire due to change in temperature. It is shown that inflating and deflating the tire is effective in making up for changes in driving condition. The influence of sensor response characteristics, such as time delay and noise, were also included in the simulation and evaluated. The time delay was estimated based on the time to obtain the deflection based on the period of the wheel spin; the influence of the time delay can be minimized by changing the proportional and integral gains. The results also suggest that the system is actually robust to the influence of noise. Some suggestions for future work on this problem are provided.

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Chapter 1

Introduction

1.1 Description of the Problem

This thesis was motivated by research and development on wheeled military vehicles that must travel through diverse terrain, where proper adjustment of tire inflation pressure can be a key factor in optimizing overall mobility and performance. When a vehicle is traveling across sandy deserts, for example, tire pressure that is lower than normal can achieve a larger contact area, lower contact pressure, and some degree of flotation.

This study endeavored to test the idea of dynamically controlling the contact area by inflating or deflating the tire with a central tire inflation system (CTIS). Here, tire-surface contact area is measured indirectly, using a measurement of vertical deflection and a model basis to infer contact area. The estimated contact area is then compared to a desired contact area, and error used to guide increasing or decreasing the tire pressure using a CTIS.

In this conceptual system, the vertical deflection of the tire is measured by three ultrasonic distance sensors mounted in parallel at the wheel hub. Figure 1.1 shows the configuration of the sensors. As the wheel rotates, the ultrasonic sensors are used to measure the distance between the wheel hub and the inner surface of the tire. The vertical deflection of the tire is then simply calculated as a measure of the difference between the maximum distance and the minimum distance. The system can take the average deflection from the three sensors so as to minimize the error. The tire contact area is then calculated based on measured deflection.

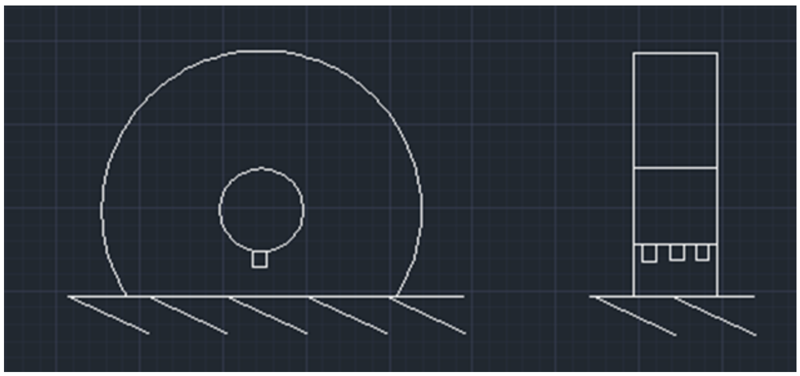


Figure 1.1: Configuration of the Sensors

In this way, we can build a feedback control for the tire contact area based on the ultrasonic distance sensors and the CTIS.

In fact, some actual tests were run for measuring the tire deflection when the vehicle is running on different types of terrains. However, there was so much noise in the measured deflection signal that the change in vertical deflection was hard to see. Solving this problem of noise may require more research into the nature of the sensors as well as the characteristics of the tire.

1.2 Background

The idea of lowering tire inflation pressure to improve the performance of the vehicle on soft terrain is commonly seen in real life. If the inflation pressure of the tire is low, the ground pressure will stay the same and the contact force of the tire is just the ground pressure multiplied by the contact area. In this way, increasing contact area on soft terrain can increase the contact force between the tire and the ground, which in turns increases traction. This is proved by a series of studies including Tridal[15] and Schwanghart[14], who studied the relationship between the contact pressure and inflation pressure on soft soil. From these studies, we note that controlling contact area is a practical way to improve mobility of the vehicle on soft terrain.

The method of measuring vertical deflection with distance sensors mounted at the wheel hub was proved effective by several researches including Magori[18] and Tuononen[16]. Magori used ultrasonic sensors and Tuononen used optical sensors, but the algorithm is the same. Both methods were proved effective on hard terrain.

Several researches have provided ways to estimate contact area based on vertical tire deflection. Upadhyaya & Wulfsohn[17] derived some succinct equations for calculating 2-D contact area based on vertical tire deflection, assuming hard terrain and elliptical contact area. Komandi[7] provided a similar result on hard terrain, but the equations were not as succinct. However, most researches were done on hard terrain. For the cases of soft terrain, the most commonly used way to get contact area is FEA. Ragheb[8] built a

FEA tire model for combat vehicles on soft terrain; however, FEA models are unlikely to be implemented in real-time control systems.

Since we need to calculate vertical tire deflection under different inflation pressure, we also need to look at some studies about the vertical tire stiffness. Cooper[4] considered the tire as two springs in parallel; in this way, the total vertical load of the tire, can be expressed as the sum of structural load and pneumatic load and the tire stiffness can also be expressed as the sum of two effective springs. Painter[12] also established a model based on the concept of equivalent contact area, but the result was more of an experiential equation including quadratic term of the deflection, which was not the most convenient for building dynamic models.

1.3 Statement of Purpose

Based on the analyses of the problem and the literature reviews, in this thesis, we aim to build a simulation of the control system so as to test the validity and limits of it. The simulation will be built under the following assumptions:

1. Hard Terrain.

   As mentioned in Section 1.2, the method of measuring tire deflection was proven effective on hard terrain. For the case of soft terrain, it is more complicated to estimate the contact area. However, since we only want to validate the idea of the control system here, we're only looking at the case on hard terrain and check if the idea is practical.

2. Elliptical Contact Area.

   In the simulation, we assume an elliptical contact area i.e. the shape of the tread is not considered. It is accurate enough for the rough estimation in this case.

3. In the vertical direction, the tire is modeled as a 1-D mass-spring-damper system with changing stiffness.

   Since the vertical stiffness of the tire changes with the inflation pressure, the vertical deflection of the tire is calculated from a 1-D mass-spring-damper model with changing stiffness.

Some tests will be done with the system to find whether the system is able to work under different driving scenarios. Also, since the real sensing process of the vertical deflection didn't work as expected, some tests will be done about the possible noise and time delay from the actual sensors.

1.4 Organization of Thesis

The thesis consists of seven chapters in total. Chapter 2 describes how a simulation under ideal case was built, with details in how different parts of the simulation works and how the constants were chosen. Chapter 3 lists the results of testing in 3 different driving scenarios and analyzes the effectiveness of the control system. In chapter 4, we're trying to include the possible influences from the sensors, adding time delay and noise to the system. Chapter 5 conducts some tests with time delay and noise from the sensors. Chapter 6 provides some discussion about the simulation and talks about possible future work on the system. Chapter 7 lists the conclusions.

Chapter 2

Simulation of the Control System

This chapter describes how the simulation was built and made to operate in order to study the performance of an automated tire inflation system. Firstly, the basic structures of the whole simulation process of the system and some basic policies in each part of the simulation are described in Section 2.1. Then, the process of building each part of the simulation model is explained, as well as the assumptions and simplifications. Section 2.3 describes how the simulation is elaborated from components to a real working simulation. Processes here include finding appropriate constants, initializing the simulation, as well as building and testing the controller.

2.1 Basic Structure

The structure of the whole model is as shown in Figure 2.1. The whole simulation model consists of the following components:

1. Central Tire Inflation System
2. Estimation of Tire Deflection
3. Estimation of Tire Inflation

4. Estimation of the Contact Area

5. Decision on desired inflation pressure

In Figure 2.1, the two major blocks represent the functions for the tire system and the CTIS. The physical system block provides an estimation of tire deflection, tire inflation, and the contact area. These three functions are put into one function since they occur simultaneously. The small blocks represent different states or inputs and outputs for the functions.

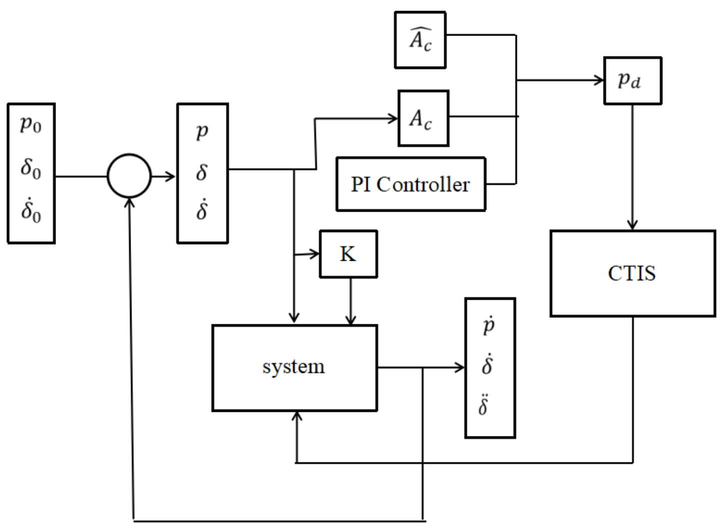


Figure 2.1: Structure of the Simulation

The algorithm starts with measurements of the tire vertical deflection δ_0 and calculates the contact area A_c. Based on the vertical deflection, and the current inflation pressure, p_0, the stiffness of the tire, K is determined and plugged into the simulation. Meanwhile, based on the difference between the calculated contact area and the desired contact area $\widehat{A_c}$, a desired pressure p_d is determined with a PI controller and sent to the CTIS. The CTIS then estimates an inflation time to reach the desired pressure, and starts inflating the tire over the estimated period of time. The deflection and pressure is measured again, and the whole process is repeated continuously.

2.2 Building the Components

This section describes the design and operation of each component in the algorithm.

2.2.1 Simulation of CTIS

The simulation of the central tire inflation system (CTIS) is based on the method described by Schultz et al. in the patent titled *Adaptive Inflation Control for Vehicle Central Tire Inflation System* [6]. The general function of the system controller is to estimate the time that the control valve should stay open. The system can adjust the function to calculate the open time by itself during the process of inflation. A simplified block diagram of the system is shown in Figure 2.2.

As shown in Figure 2.2, Schulz's method first determines an inflation time, T, based on the current pressure p_c and the desired pressure p_d. After letting the system inflate for the designated time, it measures the pressure again and compares the new pressure to the desired pressure. If the pressure

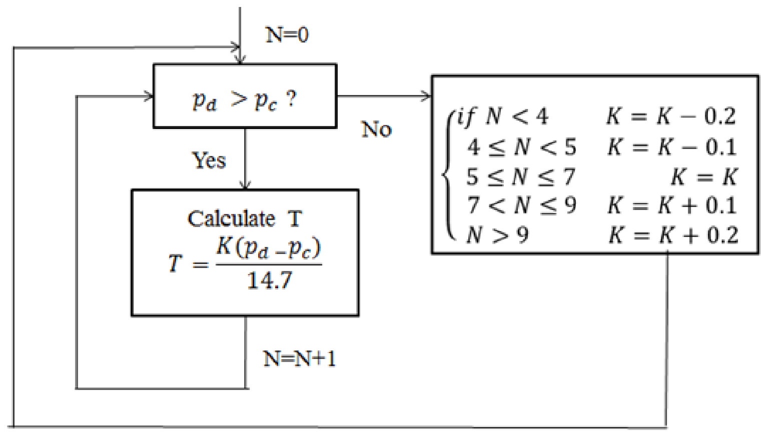


Figure 2.2: Block Diagram of CTIS

is still lower than the desired pressure, the count N is incremented. Finally when the pressure reaches the desired pressure, the system will adjust the coefficient that adjusts inflation time, K, so that the generated time will get closer to the actual time needed for the actual inflation process.

The inflation algorithm is fairly simple yet effective as a trial and error method to adjust the inflation time for a given and uncertain operating environment. With this algorithm, the system can adjust itself quickly without the need to stop working or adding extra time to make a decision. This is a great advantage, since the vehicle's operating environment (temperature, terrains, etc.) can be constantly changing. However, the system does have some discrepancies. Firstly, the tire inflation pressure may go over the desired pressure at times, which would let the tire operate under undesired and possibly dangerous conditions. Secondly, it may be possible that the system needs to run a long time in order to get the ideal K value for a given situation.

Based on the advantages and disadvantages of the system, the K value will be tested and set to a fixed value during the simulation so that the system is always running at the best condition. This is reasonable since the simulation supposes ideal conditions and developing a particular CTIS system is not the intent of this project. Meanwhile, the self-adjusting algorithm will be kept as a function for future explorations of the simulation. The related testing and results will be described in Chapter 3, and more discussions of the system will be given in Chapter 6.

2.2.2 Modeling Tire Deflection

The tire deflection estimation is based on a stiffness model of the tire, with stiffness dependent on the tire pressure. The vertical dynamics of the tire are modeled as a simple mass-spring-damper system, i.e.,

$$m\ddot{x} + b\dot{x} + kx = F(t), \tag{2.1}$$

where m represents the mass of the tire (and a representative fraction of the axle), and b is the effective tire damping, which is hard to estimate. As a result, b is typically chosen based on testing, and a typical process will be discussed in the next chapter. Therefore, the key point here is the algorithm to estimate the effective tire stiffness, k.

As mentioned in the first chapter, the stiffness of the tire can be estimated using Cooper's method [4], which extracts parameters from load-deflection curves using the relation,

$$\frac{\partial W}{\partial x} = pK_p + K_s. \tag{2.2}$$

This method is simple for determining effective tire stiffness for use in simulations. Based on the Cooper's relation above, the only parameters that are needed K_p and K_s. After that, the tire stiffness can be easily calculated by parameterizing with a given inflation pressure.

It is clear that in order to figure out the stiffness of the tire, K_p and K_s values must be determined from load and deflection measures under different inflation pressure. For this purpose, measured load-deflection data from recently reported results by Stallman[11] are used in this study. These data are summarized in Table 2.1, and a plot of the data is shown in Figure 2.3.

Table 2.1: Load-Deflection data.[11]

Load(kg) / Pressure(kPa) / Deflection(mm)	100	300	550
0	0	0	0
10	1905	3469	6354
20	4716	9445	15537
30	7221	15559	25250
40	9947	21968	36872
50	13415	29011	48446
60	17673	37581	62502
70	21582	45717	74730
80	25646	54191	88151

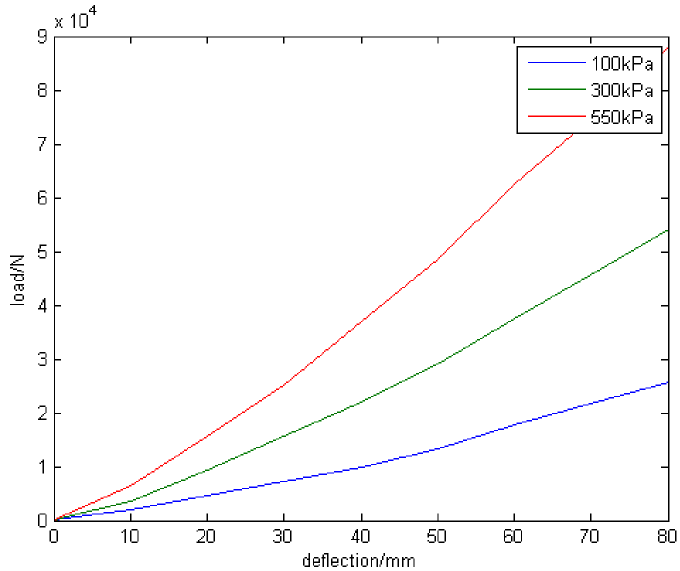


Figure 2.3: Load-deflection measures from Stallman[10]

From Figure 2.3, it is appears that the data is reasonably linear within the range of 100 kPa to 550 kPa inflation pressure and 10 kN to 90 kN vertical load. Therefore, The $\frac{\partial W}{\partial x}$ parameter values are the slopes for each linear fit. Table 2.2 shows the data for the $\frac{\partial W}{\partial x}$ values.

Table 2.2: $\frac{\partial W}{\partial x}$ vs. pressure data.

$\frac{\partial W}{\partial x}(1 * 10^6$ N/m)	Pressure(kPA)
3.23	100
66.9	300
11.25	550

With a $\frac{\partial W}{\partial x}$ vs. pressure plot, it can be seen that the data points are highly linear, which adds to the confidence in the stiffness model.

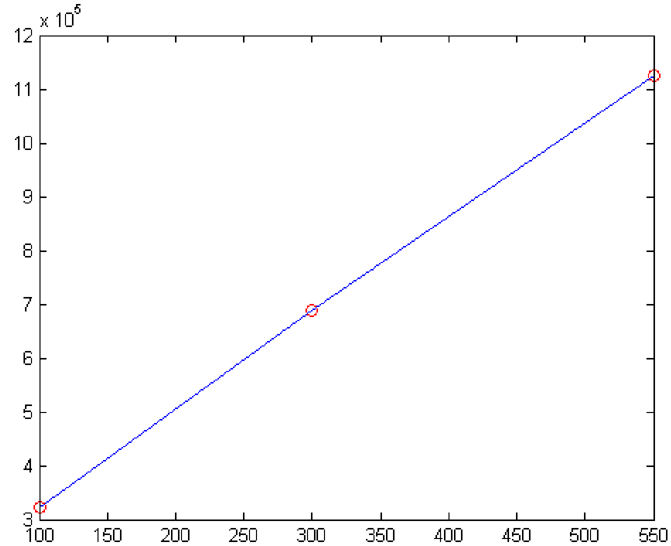


Figure 2.4: $\frac{\partial W}{\partial x}$ vs. pressure plot

Using a linear fit again, the K_p and K_s values from Stallman et al. data are found as:

K_p=$1.78 * 10^3$ N/(m*kPa)

K_s=$1.48 * 10^6$ N/m

With these K_p and the K_s values, we are able to implement a model for stiffness into the deflection estimation taking into account inflation pressure. Meanwhile, the stiffness data seem to be very reliable based on the linearity of the actual data measurements.

2.2.3 Simulation of Tire Inflation

The simulation of tire inflation can take at least two different approaches. One way is to model the air compression like a piston-cylinder. For example, Figure 2.5 shows a bond graph for a piston model from Karnopp [5]. This model includes a parameter for the area A of a straight cylinder,

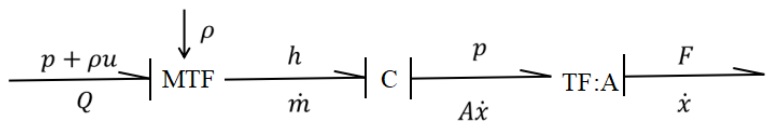


Figure 2.5: Bond Graph for the Piston Model

with the piston applying a force, F. The flow rate, Q enters the cylinder, so that the pressure of the gas (p), the internal energy of the gas (u), and the position of the piston (x) are constantly changing. This model could represent an inflating tire in that both models capture changing volumes of a 'pneumatic capacitor' subject to external force(s), air flow input, and assuming a compressible fluid (air).

In order to use this model, the following questions need to be addressed:

1. What is the effective area, A?
2. Do we need to use enthalpy, h, as a state, to track amount of air (mass) entering the tire?

The effective area in the case of the tire is changing during dynamic performance. The contact area could be a state in the estimation of the pressure, leading an additional nonlinear effect. An additional complexity is that details required for using enthalpy as a state requires more approximations. In the end, it would be preferred to use a simpler model for the purposes of this work, since the more detailed model just described would add no value to the end result. In the end, the more complex tire inflation model was not deemed practical for this study.

A more practical approach for the tire inflation model is to adopt a simple first-order system as an approximation, represented by,

$$\tau \dot{p} + p = p_{\text{inflation}} \tag{2.3}$$

where p is the tire pressure, and τ is an effective time constant, easily adopted from observed system operations or specifications. This simplified model can represent how pressure will increase (or decrease) at the start of an inflation (or deflation) process, and the rate of pressure change, $\dot{p}$ becomes gentler as the process goes on until it reaches a steady state, which is similar to the actual inflation process of the tire.

In this equation, $p_{\text{inflation}}$ represents an end pressure set for the model while inflating. This pressure should not exceed the highest pressure the tire can take for safety reasons. In the simulation, this pressure was set to be 550 kPa, as implied by the specifications of tires used for large off-road vehicles. The value of τ dictates the inflation rate. Determining a suitable time constant is discussed in Section 2.2.5.

Using the first order system approximation, the inflation pressure can be simulated without adding too much complexity to the system model. This approach assumes that, a) the inflation process can be characterized by a known time constant, and b) the inflation process is well-approximated by a linear process. Based on the time scale (in minutes) and the range of tire pressure in the simulation, this approach should provide a reasonable simulation for the purposes of this work.

2.2.4 Calculating Contact Area

The tire-surface contact area is estimated based on work by Upadhyaya and Wulfsohn [17]. According to Upadhyaya and Wulfsohn, an elliptical contact area is sufficiently accurate for non-deformable terrain applications, providing a reasonable estimate for this simulation study.

Upadhyaya and Wulfsohn's method offers a way to estimate contact area based on vertical deflection of the tire, δ_z. The system then calculates the contact area in the following steps:

1. Calculate deflection,

$$\delta_z = l_{min} - R_1 \tag{2.4}$$

   R_1 - Radius of the tire

   l_{min} - The minimum vertical distance between the tire tread and the wheel hub in a round

   δ_z - Vertical deflection

2. Then determine the contact length

$$l_c = 2d\sqrt{\frac{\delta_z}{d}} \tag{2.5}$$

d Diameter of the tire

3. Contact width is,

$$l_w = \begin{cases} 2\sqrt{2}\xi R_2\sqrt{\frac{\delta_z}{R_2}} & if \quad l_w < w \\ w \quad if \quad l_w \geq w \end{cases} \tag{2.6}$$

R_2 Tread radius

w-tread width

ξ- an experimental coefficient

4. Contact area is,

$$A_c = \frac{1}{4}\pi l_c l_w \tag{2.7}$$

With equations (2.6) and (2.7), the calculation of contact area can be easily implemented in the simulation as,

$$A_c = \begin{cases} \sqrt{2}\pi\delta_z\sqrt{dR_2} \quad if \quad l_w < w \\ \frac{\pi}{2}\sqrt{d\delta_z}w \quad if \quad l_w \geq w \end{cases} \tag{2.8}$$

The Upadhyaya & Wulfsohn approximation is a simple way to calculate the contact area and easy to plug into the whole simulation. This model assumes elliptical contact area on hard terrain, which may need to be substituted by other estimations in any extension to other terrain types.

2.2.5 Deciding Desired Pressure

The desired tire inflation pressure is based on calculation of the K_p in the stiffness part. If the desired A_{cd} is larger than the actual contact area A_c, a higher p_d based on the desired K_p will be calculated and sent to the CTIS. In order to get a better result over time, a parameter similar to the K in the CTIS is also added here to moderate the p_d over time. The K value will also be optimized through the testing in the actual simulation, just as the K value in the CTIS model. The algorithm itself will also be kept for making adjustments of the system.

In addition, the original CTIS only manages inflation pressure. However, based on the requirements of the system, the actual simulation includes controlled inflation and deflation. This is achieved by adding a deflation side to the inflation function. After adding the deflation function, the CTIS in the simulation works in the following steps:

1. Determine if the current inflation pressure is within a tolerable range from the desired pressure.

2. If the current pressure is lower than the desired pressure, set the inflation pressure to be 550 kPa and start inflating until the air pressure reaches the desired pressure; if the current pressure is higher, set the inflation pressure to be 100 kPa and start deflation.

3. Count how many times the system has to reset the inflation time and adjust the K value accordingly.

2.3 Elaborating the Simulation

Section 2.2 mainly discussed the structure of the simulation and described how different parts of the simulation were designed. However, in order to make the simulation work, there is some necessary preparation work, namely:

1. Deciding Tire Damping Coefficient and Time Constant
2. Initializing the Simulation
3. Setting System Parameters
4. Adding the Controller

This preparation work is explained in this section.

2.3.1 Deciding Tire Damping Coefficient and Time Constant

The tire damping coefficient, b and the time constant in the inflation model, , are parameters that cannot be directly found from available references or specifics. These are not parameters that can be determined before the actual simulation is developed. The process for determining each of these parameters is described below.

The tire damping coefficient, b, is an important parameter in modeling the change in vertical tire deflection. However, it is not included in the specifications of a tire. This is probably because it is hard to measure the damping coefficient directly since tire damping comes from the dynamic response effects in tire deformation. Moreover, it is also possible that the damping ratio is changing while the operating environment of the tire changes. These changes include speed changes of the vehicle, temperature changes, and the aging of the rubber. Due to all of these uncertainties, the damping coefficient of the tire cannot be easily listed as a rated value in the tire specifications.

Fortunately, in the simulation, it is not necessary to model the damping coefficient with so many details since the main changes in the deflection are related with the tire stiffness. The damping coefficient will be modeled as a constant which allows the tire to rest at a fixed rate quickly after a sudden excitement. A reference value is found from related references, and testing of the reference value is performed to make sure that the value works normally.

In order to find a good value for reference, some research into tire damping as used in vehicle suspension systems was conducted. Most studies on tire dynamics didnt explain exactly where the parameters they used came from. They simply give a list of their parameters. For example, in an analysis of half-car active suspension done by Türkay and Akcay [13], the list of parameters is as given in Table 2.3. This table contains parameters for the suspension and the tire. Judging by the magnitudes of the numbers, it is obvious that this research was done with a much smaller tire than a normal tire. However, this data can still work as a good reference if we calculate damping ratio, ζ, from the given damping coefficient, stiffness and mass data. The ζ value should be similar in different tire models since it is dimensionless and unrelated to the

Table 2.3: Suspension Parameters from Reference [13]

Sprung mass	500kg
Pitch moment of inertia	2700 $kg * m^2$
Unsprung masses	36 kg
Damping coefficients	980 Ns/m
Suspension stiffness	1600 N/m
Tire stiffness	160,000 N/m

size of the tire. ζ can be calculated from the following equations:

$$\zeta = \frac{b}{2m\omega_n}, \tag{2.9}$$

where $\omega_n = \sqrt{\frac{k}{m}}$ is the natural frequency of the system.

The tire damping ratio used in the cited study was 0.204. Other studies, including Stallman[10], use a similar value, 0.193. Therefore, the tire damping ratio in the simulation was made 0.2. The damping coefficient is then calculated with a nominal stiffness for inflation pressure of 550 kPa, which is 1.13×10^6 N/m, giving a damping coefficient of 6.58×10^3 Ns/m.

The time constant, τ, will dictate the inflation time in the tire inflation model. As mentioned in the previous chapter, the inflation system is assumed to have first order system dynamics. As a result, a τ value is the only parameter that is needed to model the inflation process. Therefore, it is necessary to find an appropriate value for the τ value in order to have a good estimation of the inflation state.

In order to at least get a reference for the approximate inflation time, some commercial tire (off-the-shelf) inflators were studied. The Goodyear 120V multi-purpose inflator, and its specifications indicate that the approximate inflation time for a 14 inch tire from normal air pressure to 28 psi (about 193.3 kPa) is about 2.5 minutes. This is considered a reasonable reference value for inflation time, since even if larger CTIS systems with more power it is not likely that the inflation process will be faster due to the fact that the actual tire in consideration is much larger and more stiff than the 14-inch tire.

The τ value was decided through trial and error testing. After a series of tests, the time constant chosen for the simulation model was set to be 600 seconds. As a result, the time for the inflation process from 100 kPa to 200 kPa will be about 100 seconds.

2.3.2 Initializing Tire Deflection

Initializing the tire deflection means identifying the initial tire deflection and setting it as the new initial value of deflection. An actual tire on the vehicle is experiencing some vertical load and deflected from the start. In order to get this initial deflection, the tire deflection model was given a vertical load in the form of a step input. Then, the equilibrium deflection value is found and used as the initial deflection value in the actual simulation.

The conditions used in this test are shown in Table 2.4 and typical response results for an initialization testing are shown in Figure 2.6.

From the plot in Figure 2.6, we can see that there are some initial oscillations before the tire finally rests at a deflection of 52.28 mm. The oscillation

Table 2.4: Conditions for Initializing Tire Deflection

Vertical Loads	58.9 kN
Initial Deflection	0mm
Tire Pressure	550 kPa

is a result of the vertical load, applied in the form of a step input and the transient is not relevant for the purposes of this work. The deflection value is in an acceptable range, according to results published by Stallman [11], which suggests 50-60 mm deflection for a vertical load around 48 to 62 kN. Therefore, 52.28 mm was set as the initial deflection for the tire under study.

2.4 Setting Right Parameters

Another testing result we should look at here is the contact area. From the measurements by Stallman, the tire contact area on a rigid surface for an inflation pressure of 500 kPa at a load of 58.9 kN is 0.147 m^2. During these studies, it was found that if the value of ξ, an experiential coefficient for estimating the length of the tire contact, l_w, was set to 0.737, the simulated contact area would just match the result in studies by Stallman. The result for the contact area is shown in Figure 2.7. According to Upadhyaya and Wulfsohn [17], the ξ values from two of their own experimental tests were 0.782 and 0.629, which means that a value of 0.737 is acceptable.

Another value needed here is the initial K value for estimating the inflation time in the CTIS function. In addition, the CTIS function should also

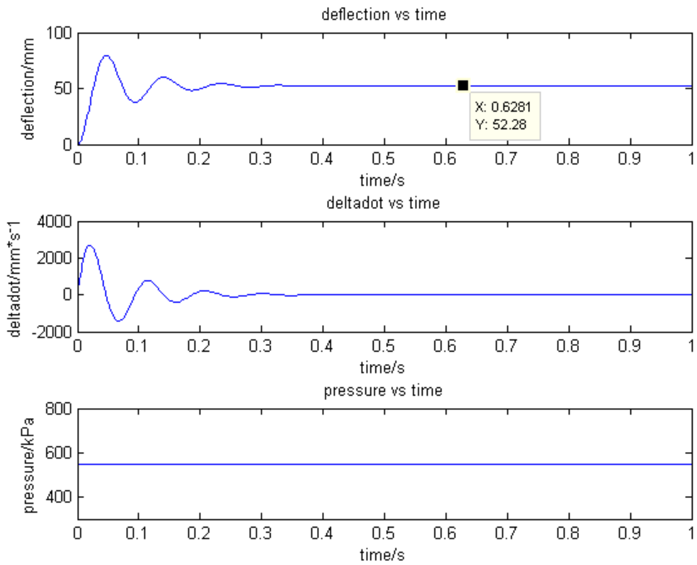


Figure 2.6: Initializing Tire Deflection

go through test runs to ensure that it is working properly. Schultz's CTIS[6] decides the K value through repeated inflation tests. It first generates an inflation time, say t_1, with any given K and starts inflating. After inflating for t_1 seconds, it measures the current pressure and compares it to the desired pressure. If the current pressure is still lower, it will generate another inflation time t_2. This process is repeated until the desired pressure is reached. After that, the system counts the repetition, and adjusts the K value based on the count. In the patent by Schulz, the K value is considered as optimized when the system has to generate 5 to 6 inflation times for any given desired pressure. This is probably to prevent the system from giving too large an inflation time at the beginning. A similar approach has been adopted in the simulation.

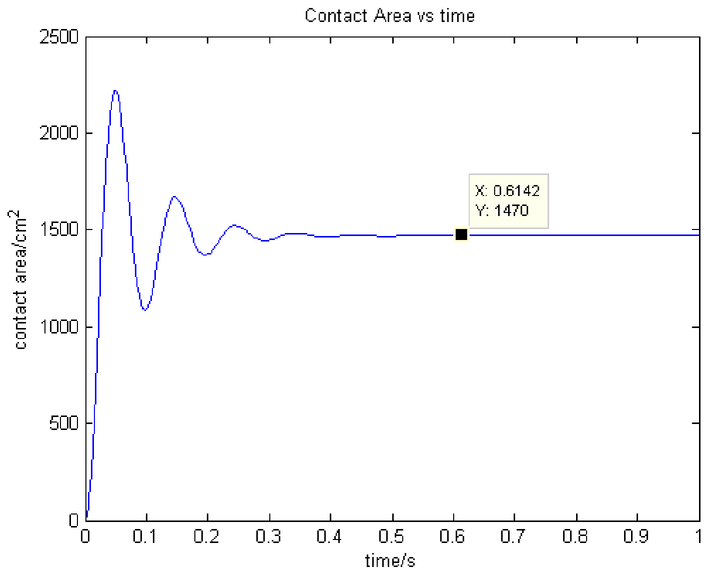


Figure 2.7: Contact area model estimation

The patented process proposed by Schulz, for adjusting the K value, is meant to be adaptive for unknown inflation system properties. It will continue to adjust the inflation parameter several times before a relatively stable K can be reached. To demonstrate this in testing, a stair-step signal is used as the desired pressure signal. The signal starts at 300 kPa and ends at 550 kPa, and increases 10 kPa by every 50 seconds. This will allow the CTIS to run 25 times from one single inflation process. The result of an inflation test is shown in Figure 2.8.

During the test, it was found that the K value never actually reaches a steady-state value. The CTIS is constantly modifying itself. Therefore, only a certain range of initial K value can be specified such that a stable value of

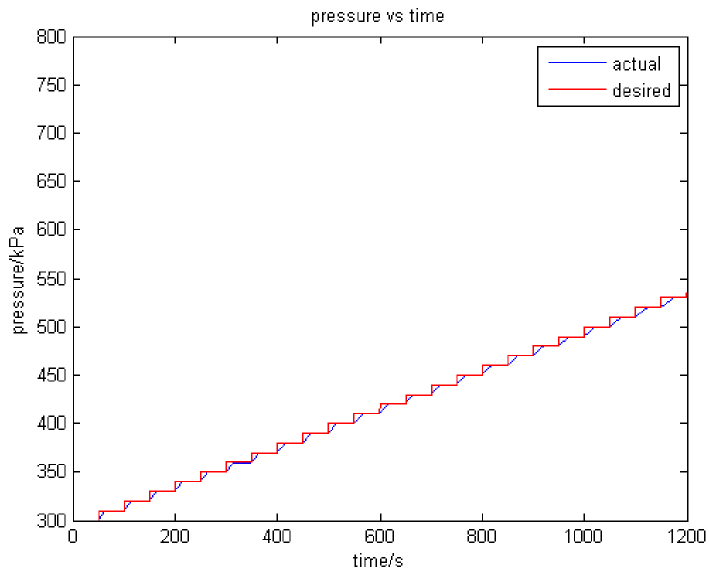


Figure 2.8: Test to Find the K Value (Inflating)

K will be reached by this process. After several trials, it was found that if the initial K value was set to around 143, the output K value stayed around 141 to 145. Therefore, the initial K value was determined as 143.

The original CTIS is only designed to inflate the tire. However, in the simulation developed here, the CTIS is extended to actively deflate the tire as well. The system will switch to a deflation mode if the desired pressure is lower than the current pressure. The deflation process is similar to the inflation process, and the lowest deflation pressure was set to be 100 kPa. A tolerance (hysteresis gap) of 0.1 kPa was allowed, so that the system will not frequently switch between inflating and deflating when the pressure is close to the desired point. After adding deflation to the function, another test for the K value in deflation was conducted, and the value was also found to be around 143. Figure 2.9 shows the K value test for the deflation case.

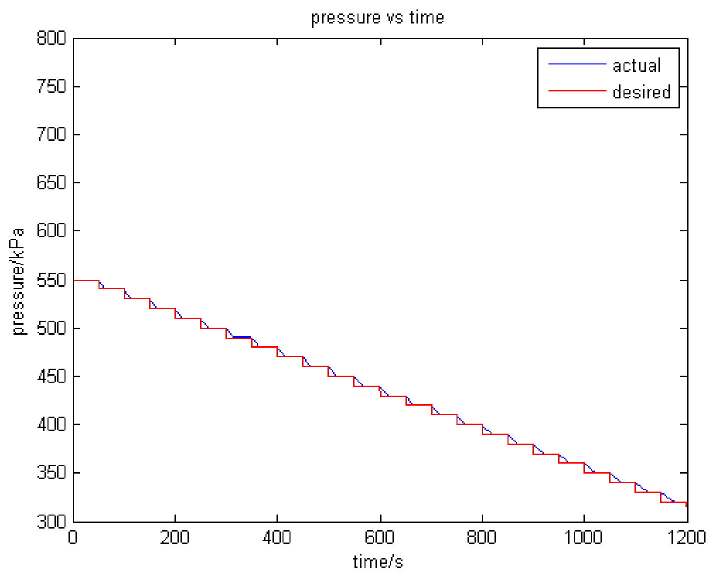
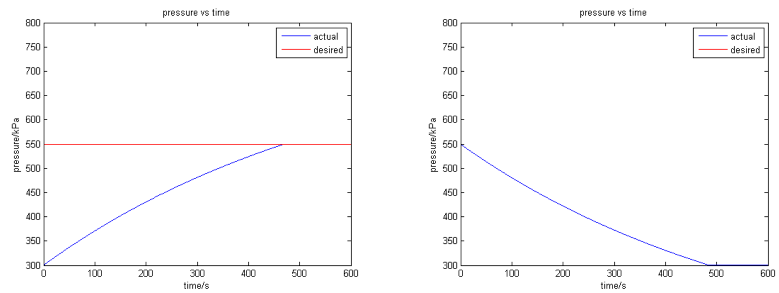


Figure 2.9: Test to Find the K Value (Deflating)

With nominal K values determined, inflation/deflation tests with fixed desired pressures were conducted to make sure that the inflation times were reasonable. Figure 2.10 shows results from typical inflation /deflation tests.

From Figure 2.10(a), it can be seen that the inflation time from 300 kPa to 550 kPa is about 480 seconds, which is close to earlier predictions. This means that the CTIS is not adding much delay to the simulation. Similarly, the deflation time was also found to be around 480 seconds. Figure 2.11 is the change in deflection and contact area during the test. The trends and the numbers for these variables are also looking reasonable.



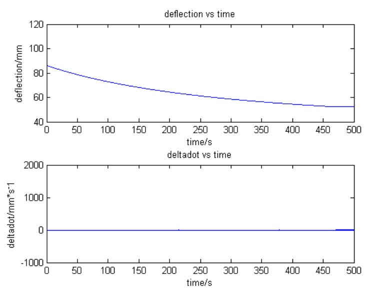
(a) Inflation (b) Deflation

Figure 2.10: Inflation/Deflation Tests

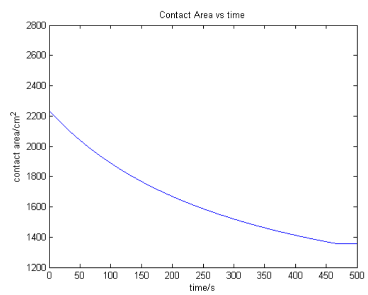
2.4.1 Adding the Controller

After the system can successfully perform the inflation/deflation function, we can finally add the controller function to the simulation. The controller reads the current contact area and compares that to the desired contact area under a certain operating environment. The controller then decides a desired pressure for the system and the system starts inflating or deflating the tire.

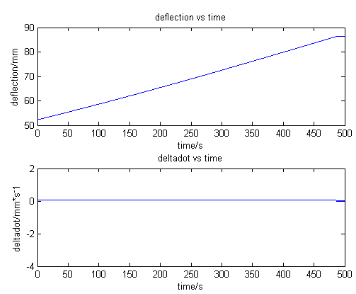
The initial idea was to add a controller working with a similar principle as the CTIS system; i.e., generating a desired pressure based on the K value and adjusting the K value through the inflation process. However, from the results of the inflation/deflation tests, it seems that this process of changing the K value is fairly slow. As a result, the process of changing the K value in deciding the desired pressure is abandoned in this controller. The gains in the controller were set to fixed values during one test, and changed manually for different runs so that the best value was found.



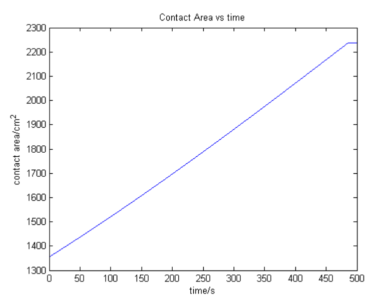
(a) Deflection @ Inflation



(b) Contact Area @ Inflation



(c) Deflection @ Deflation



(d) Contact Area @ Deflation

Figure 2.11: Deflection and Contact Area Change in Inflation/Deflation Tests

The controller for contact area to be used here is a PI controller. The transfer function for the controller is,

$$\frac{p_d - p}{A_{cd} - A_c} = \frac{\Delta p(s)}{\Delta A_c(s)} = K_P + \frac{K_I}{s} \tag{2.10}$$

where $\Delta p(s)$ is the output, which is the desired pressure, p_d, subtracted by the current pressure, p. Δp is defined this way so that it can be directly added to the current pressure to get p_d. The input is ΔA_c, which is the difference between the current contact area and the desired contact area. This is defined as $A_c - A_{cd}$ so that the K_P stays positive. K_P and K_I are the proportional and integral gains respectively.

A final step to is to determine reasonable values for the K_P and K_I gains. A test is conducted with a step input of contact area at 1400 cm^2. After testing different combinations of the two gains, a good combination is found at K_P=800 and K_I=10. The testing results are shown in Figure 2.12. With this combination, the overshoot was found to be 6.67% and the settling time was 44.65s for the contact area change from 1352 cm^2 to 1400 cm^2.

With a working controller added to the simulation, the simulation can now control the contact area according to the demand.

2.5 Conclusion

This chapter describes how a simulation model is formulated from scratch, including the structure of the simulation, how each part of the system is built, and how the simulation was parameterized in order to produced

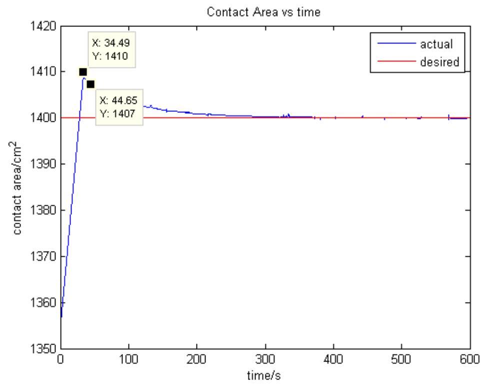


Figure 2.12: Result of Contact Area Control

realistic response. In the next Chapter, test results from using the simulation model are be presented and evaluated.

Chapter 3

Simulation Results

In Chapter 2, a working simulation of a system for controlling the tire-surface contact area based on feedback from estimated tire deflection using a tire inflation model has been described. In this chapter, the simulation is used to demonstrate controlling the contact area under different scenarios. The scenarios are chosen to mimic driving conditions that might lead to varying contact area in the tire-surface interaction, namely:

1. sudden change in terrain stiffness, simulated as a sudden change in the desired contact area,
2. changes in vertical applied load, and
3. pressure changes in the tire caused by the change in temperature.

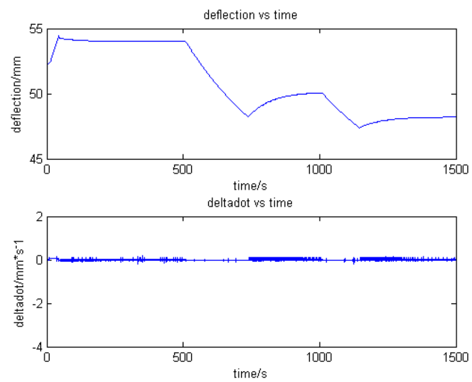
The results from the simulation studies will show the controller's ability to change or stabilize the contact area under each scenario. The results are meant to approximate what might happen in real-life operating conditions.

3.1 Testing with a Sudden Change in Demand of Contact Area

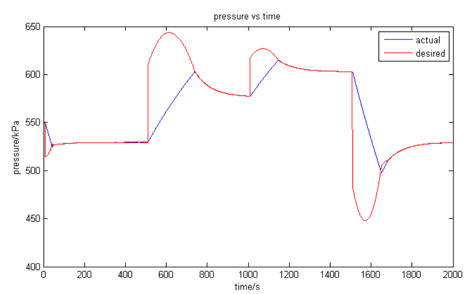
A sudden change in contact area is one way to simulate the terrain suddenly changing. Traction characteristics between the tire and the ground surface changes with the type of the road and terrain. However, if the contact area can be controlled actively, it may be possible to optimize the tire-surface interaction properties for different terrains. As a result, the performance of the vehicle can be optimized on different types of terrains.

In this scenario, the simulation starts at a nominal working point ($F =$ 58.9 kN, A_{c0}=1352 cm^2, $p =$ 550 kPa). At times 10s, 510s, 1010s and 1510s, the target contact area is changed to 1400 cm^2, 1300 cm^2, 1250 cm^2 and 1400 cm^2, respectively. The corresponding changes in deflection, pressure and contact area are shown in Figure 3.1.

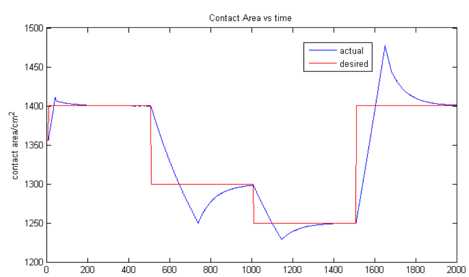
From Figure 3.1(c), we can see that the inflation pressure can be controlled so that the contact area can follow the desired contact area over a certain period of time. However, the deflation process is relatively slow compared to the inflation process. The overshoot is generally larger when the change in the desired contact is larger, which is considered normal. In the inflation process for changing from contact area of 1352 to 1400 cm^2, the 5% settling time was about 100 seconds; meanwhile, in the deflation process for 1300 to 1250 cm^2, the 5% settling time was about 330 seconds. Comparing to Figure 3.1(b) around the same time period, it can be seen that there is not much difference in the trend of the desired pressure, which indicates that the



(a) Deflection



(b) Pressure



(c) Contact Area

Figure 3.1: Deflection, Pressure and Contact Area Results for Scenario 1

difference is not likely to be caused by the controller. Possibilities are that this may be the result of the discrepancy in the inflation/deflation model, or that the controller doesn't fit well to the deflation side. More details on this discrepancy will be discussed in Chapter 6.

Another thing to note here is that the desired contact area commands are only arbitrary numbers. The desired contact areas on different types of terrains might be established through experience or experimental testing and put into a system database before application.

3.2 Testing with Changes in Vertical Load

A step change in vertical load can be a simulation for vehicle load changes, or also the case of a flat tire. For example, in the case of dual tires on heavy trucks, a flat tire would induced a step change in load on the other tire(s). A vertical load change will cause a change in the tire deflection, which can influence traction, ride, and handling properties of the vehicle. In order to restore the deflection, the tire needs to be inflated properly. In some conditions, this functionality can also support a 'limp home' strategy in the case of disabling flat tire conditions.

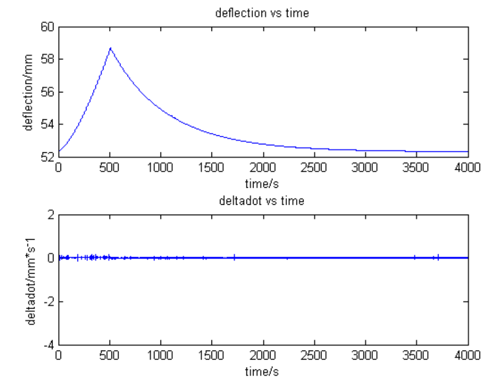
Considering the case of dual tires, there are then four wheels on one axis. Ignoring change of load between different axles, if one tire loses the ability to bear vertical load, the load will shift to other tires on an axle, for example, leading to 4/3 the original vertical load on each. Two situations are simulated for this scenario. The first situation assumes that one tire gradually loses the ability to bear load, which simulates a situation where the tire has a leaking valve and is gradually losing pressure. The second situation assumes that one tire suddenly loses all its ability to support any load, which is the case when the tire has experienced exterior damage (i.e., a blow out).

The results for the first situation, a slow tire leak, are shown in Figure 3.2. In this case, the vertical load condition changes in 500 seconds.

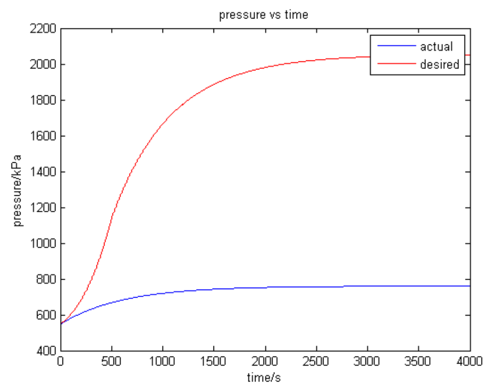
From Figure 3.2(a), it can be seen that the deflection first goes down from a normal 58 mm to 52 mm in the first 500 seconds, when the bad tire is constantly deflating. After that, the system restores deflection slowly to 58mm. A maximum of 6mm difference in the tire radius is rather small, so we can assume that the vehicle would not be destabilized by this change, so the control method is clearly useful under this situation.

In Figure 3.2(b), we can see that the desired pressure changed as soon as the vertical load started to change. This shows that the system starts working as soon as the abnormality is sensed. The desired pressure rises quickly above the high-pressure limit but the inflation process is comparatively slow. This is because the tire pressure is close to the limit. Therefore, there is a possibility that if the high limit is reached before the contact area is restored, the pressure will just stay at the high limit and the difference in deflection cannot be controlled.

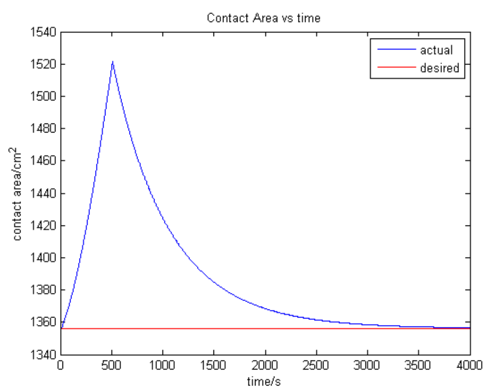
The results for the second situation is shown in Figure 3.3. To avoid too large a change in deflection and contact area, the abrupt tire state change



(a) Deflection



(b) Pressure



(c) Contact Area

Figure 3.2: Simulation Result of a Slow Rise in Vertical Load

is modeled as a vertical load change to 4/3 the original value in 5 seconds.

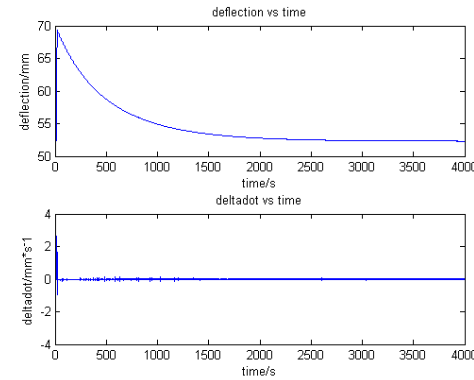
From Figure 3.3(a), it can be seen that the peak value of the deflection immediately after the induced change was about 69 mm, which means a 16 mm difference from the normal condition. The deflection is restored to 55 mm in 1000 seconds, which is comparatively slow. Therefore, if the vehicle can bear the initial 16 mm difference, the vehicle may be able to operate under this situation and the method is still feasible. The process of restoring the deflection is relatively slow, but it will cause less wear to the remaining tires in the long run.

3.3 Testing with a Rising Pressure

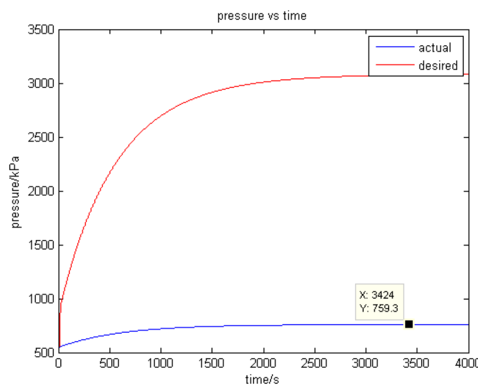
During actual driving, the pressure on the surface of the tire may increase as a result of friction or temperature change in the environment. These would cause changes in the tire pressure and therefore change the contact area. This scenario is designed for testing the controller's ability to maintain the contact area at the same value under these types of cases.

The temperature change here can be modeled as a change in the pressure rate, $\dot{p}$. Assume uniform rise in temperature over time, so the pressure in the tire is also increasing uniformly. Assuming negligible change in the tire volume, we can model this pressure change as a function of pressure added to the $\dot{p}$ item. The added term was set as,

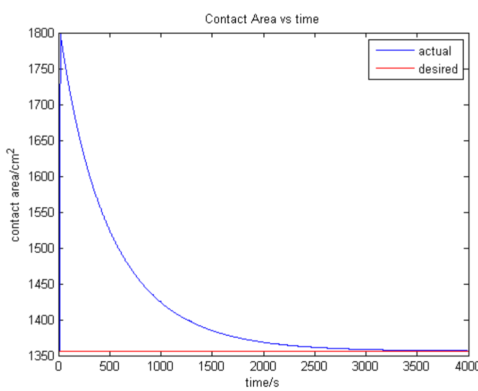
$$\dot{p} = \frac{80}{313} p/3600 Pa/s \tag{3.1}$$



(a) Deflection



(b) Pressure



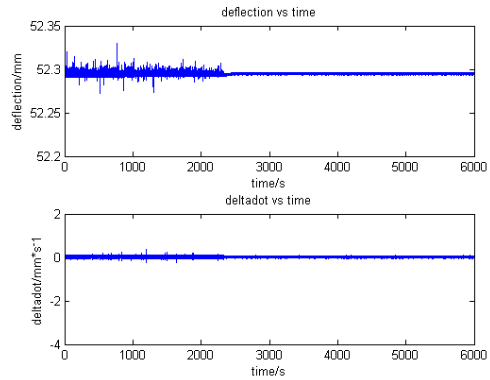
(c) Contact Area

Figure 3.3: Simulation Result of a Sudden Rise in Vertical Load

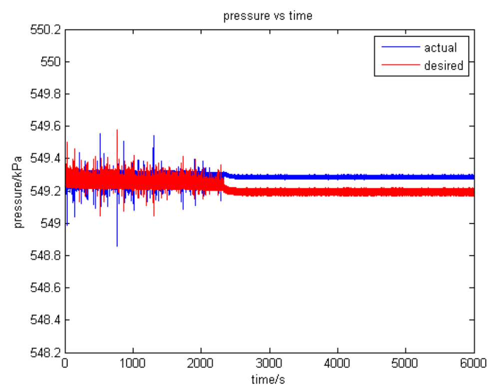
This added $\dot{p}$ corresponds to an 80°C/hour change in temperature when the initial temperature was 40°C. In the real world, this kind of temperature change is a rather slow process. However, in the simulation, the process is accelerated so that the trend can be seen more clearly. Figure 3.4 shows the results of a test in 6000 seconds.

From the plots, it can be seen that the pressure changes in the first 2400 seconds are high oscillations. This is because the pressure change was not far from the allowed floating range of pressure set for the CTIS. As a result, the CTIS was switching quickly between inflating and deflating. After a while, when the actual pressure is deviating farther from the initial pressure, the system sets a constant lower desired pressure than the current pressure, so that the tire keeps deflating a little and the pressure stayed at the same level with smaller oscillation. The same trend is observed in the contact area.

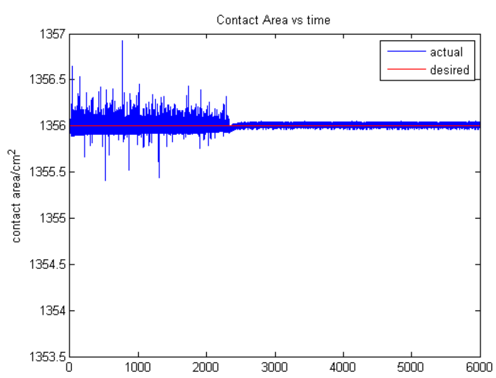
Again, the temperature rise was accelerated greatly in this test. In real life, it can be estimated that the pressure change caused by temperature changes will trigger the inflation/deflation process less frequently. Therefore, we don't have to worry about the oscillation observed in the first period of the simulation. However, if this function is needed under some extreme conditions, like the vehicle is constantly running for a long time, the system should work properly in regulating the contact area at the same level.



(a) Deflection



(b) Pressure



(c) Contact Area

Figure 3.4: Temperature Change Test

3.4 Conclusion

This chapter summarizes testing of the functionality of a control system to change or stabilize the tire-surface contact area under different scenarios. The three scenarios were: change in terrain, tire failure, and change in temperature. The simulations showed that the system was effective (or at least partially effective) in all three scenarios. However, the processes were generally slow. This is partly due to the nature of the inflating or deflating process. Naturally, more tests and experiments would be needed if the function was going to be applied to a real vehicle, but these models and simulations provide some initial insights.

During the process of testing, some discrepancies in the system behavior were also revealed by the simulation. In chapter 6, the discrepancies of the model, such as the simplification of the inflation process, are identified and discussed.

Chapter 4

Modeling the Influence of the Sensor

In Chapter 2 and Chapter 3, a simulation was built for the case of ideal sensors, i.e., the influence from the discrepancies of the sensor on the deflection signal were not considered. The simulation for ideal sensors is meant for exploring the ideal performance of the method of controlling tire contact area by changing inflation pressure based on the measurements of vertical tire deflection. However, in real-life application, the influence from the sensor can not be ignored. This chapter analyzes the discrepancies of the sensors and describes how these discrepancies can be modeled.

4.1 Analysis of the Sensor

From the original problem description, the sensor for measuring vertical deflection are three ultra sonic sensors mounted at the wheel hub. This method introduces time delay and noise to the feedback signals. In this section, the magnitudes of time delay and noise are established.

4.1.1 Time Delay

The time delay is caused through the process of measuring deflection. The ultrasonic sensors detect the distance from the wheel hub to the inner wall of tire tread. After collecting this distance in one measurement cycle, tire deflection can be estimated by the maximum distance minus minimum distance in the cycle, which means that the deflection data is collected at the wheel rotation rate. Other possible time delays from processing by the instrumentation and reading data are assumed comparatively small. Therefore, here we mainly consider the time delay caused from collecting distance while the wheel completes a rotation so that deflection is estimated.

In order to calculate the deflection signal time delay, we need the approximate time for the wheel to complete a rotation. For high speed operation, we a nominal vehicle velocity is assumed to be about 80 km/h (50 mph). For this study, the radius of the tire is 670.6 mm[2]. The wheel rotational speed can then be found to be 316.6 r/min, which makes the time of a single rotation as 0.19 second. In the simulation, we use a time delay of 0.2 second to model the time delay from the sensor. The 0.2 second time delay here is just a reference. At lower vehicle velocities, the time delay will increase.

4.1.2 Noise

In the problem concept, the sensors proposed for measuring vertical deflection of the tire are ultrasonic sensors. An earlier feasibility study on using ultrasonic sensors to measure vertical deflection of a pneumatic tire was described by Magori [18] in 1998. Another commonly used sensor for measuring tire deflection is an optical sensor. Figure 4.1 shows a sample signal for vertical tire deflection in one cycle measured with optical sensors by Tuononen [16].

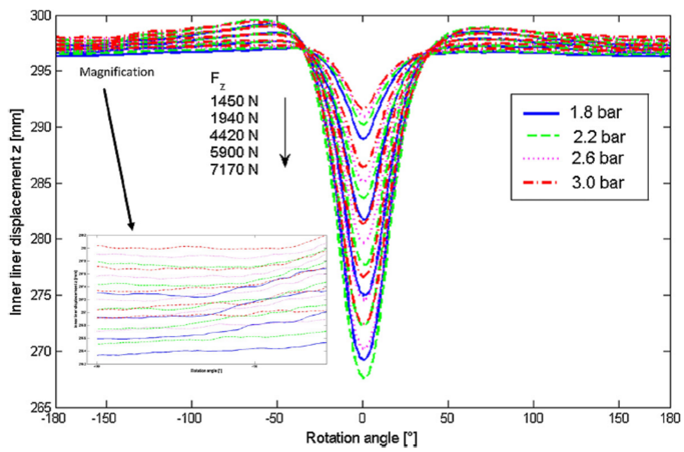


Figure 4.1: Signals from optical sensors[16]

Figure 4.2 shows a sample signal for vertical tire deflection in one cycle measured in experiments by Magori et al. From the figure, it can be seen that the signals show the trend of vertical deflection clearly. The maximum deflection can easily be found from the signal. However, the signal does have some noise compared to the signal from optical sensors.

Comparing the signals from the two types of sensors, it is clear that the ultrasonic sensor is introducing more noise than the optical sensors. However, ultrasonic sensors do have some advantages for this application:

1. It is easier to mount ultrasonic sensors inside the tire. The inner surface

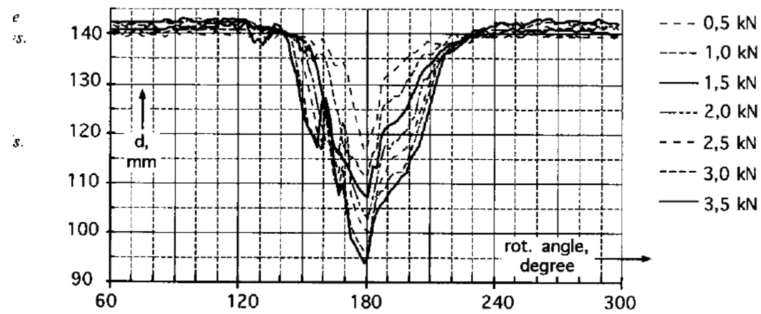


Figure 4.2: Signals from ultrasonic sensors by Magori et al [18]

of the tire can make an echo itself. If we use optical sensors, we may have to mount reflective surfaces inside the tire tread.

2. Ultrasonic sensors are much cheaper in cost compared to laser sensors. A low cost ultrasonic sensor can range from \$20-\$40 [add reference].

Therefore, if we choose to use ultrasonic sensor, we have to figure out how the behavior of the system and how it may be influenced by noise level in the ultrasonic sensor output signals.

In the process of measuring tire vertical deflection, possible sources of noise are:

1. Common electrial noise from an electromechanical sensor.

   This should be comparatively small; also, it can be easily modeled as white noise.

2. Irregular reflections.

When the tire is rotating, the geometry of the tire changes. It is possible that the ultrasonic sensor is picking up the echo from the wall of the tire. Also, since there are metal wires built in the tire tread, it is also possible that the sensor is picking up the echo from the wires. The noise from irregular reflections is much harder to model since we don't know the average power of the noise.

The actual noise in sensing the tire reflection may be from either source or a combination of both.

In the simulation, the noise from the ultrasonic sensors were modeled as white noise of different amplitudes. The amplitude will be increased and the maximum level of noise that the system can take will be assessed.

4.2 Modeling the influence of the Sensor

This part will describe how the time delay and noise are added to the model. The process is divided into three steps:

1. Preparation work.
2. Adding time delay.
3. Adding noise.

The following sections will give some details on these three steps,

4.2.1 Preparation

The simulation built in Chapter 2 worked smoothly for cases without delay and noise. However, it was built in MATLAB as ODEs in the form of MATLAB functions. The calculation process was step-by-step, making it hard to add time delay as required here. Meanwhile, it is easy to add noise and time delay in Simulink. Therefore, a necessary preparation for adding noise and time delay is to rebuild the simulation in MATLAB/Simulink, which provides convenient means for modeling both of these processes in a simulation.

Originally, all the components of the simulation were included in the same MATLAB function, including the tire deflection model, inflation model, calculation of tire contact area, simulation of the CTIS and the controlling unit. The simulation was built this way so that every state that changes with time could be updated simultaneously. However, if we want to simply use this function as a MATLAB function block in Simulink, this function is not ideal since too many inputs and outputs of the function are bundled together. In addition, the original function used global variables to define the initial value of desired pressure, which is not as easy to realize in Simulink as in MATLAB.

In order to fix the problem with ports, the input x and outputs $xdot$ and y in the original function were broken down into separate ports. The derivatives of the states, originally $xdot$, were integrated separately outside the function and then put back as x.

For desired pressure, the initial value is now defined locally inside the function when $t = 0$; after $t = 0$, the calculated desired pressure is fed back to the function through a new port called *pd_minus*. Figure 4.3 shows the new configuration in Simulink.

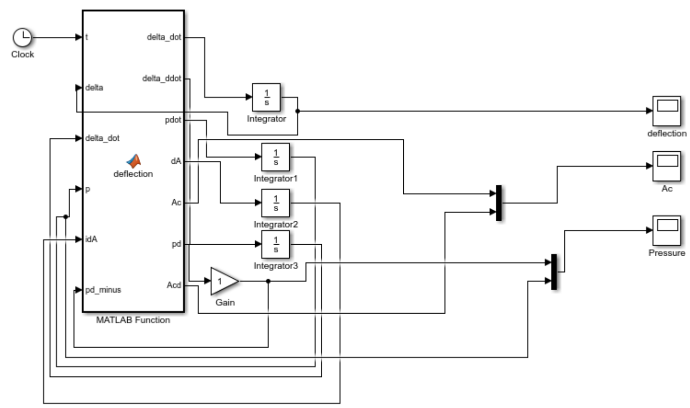


Figure 4.3: Simulink model configuration

In this model, the main block was the main MATLAB function that calculated the derivatives of vertical tire deflection, inflation pressure and the contact area based on the values of the states. The PI controller was also implemented in this block. The derivatives were then integrated and put back as states in the model. Three scopes were inserted to monitor the values of tire deflection, contact area and pressure.

To validate the Simulink model, test one in Chapter 3 was repeated. The results are shown in Figure 4.4, which show that before time delay and noise was applied the outputs from the model were the same from using the original MATLAB scripts. This verifies the effectiveness of the Simulink model.

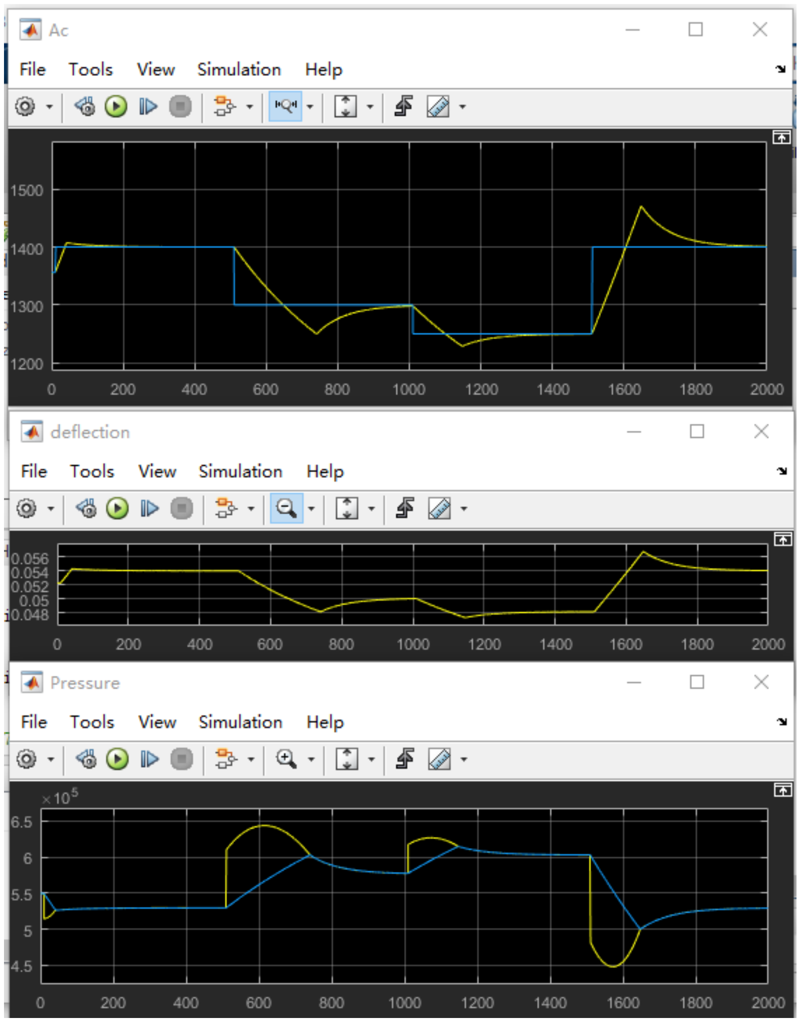


Figure 4.4: Results from Original Simulink Model

Now, we can safely draw the conclusion that any difference between the results from the Simulink model and the MATLAB scripts result from time delay and noise.

4.2.2 Adding Time Delay

The time delay was added to the Simulink model shown in Figure 4.3 using the variable time delay block. Since the 0.2-second time delay only occurs when we try to measure the vertical deflection of the tire, the time delay block was only added to the output from the deflection integrator. After the integrator was added, we repeated the first simulation test with the time delay value set to 0. The model showed the same results as before.

We tried the same test with smaller time delay value than actual, namely 0.005 second, and the model was working normally. However, when a time delay of 0.2 second was introduced into the model, it caused too much error and the model stopped working, making any further adjustments impossible. Therefore, a limit was set to the range of the vertical deflection from integration to at least keep the model moving. Figure 4.5 shows the new configuration after the saturation block was added.

The saturation block did not fix the problem completely, but it at least kept the model working with 0.2 second time delay. More adjustment to the controller was needed to get a good result for the controlled outputs. Details of this process are discussed in Chapter 5.

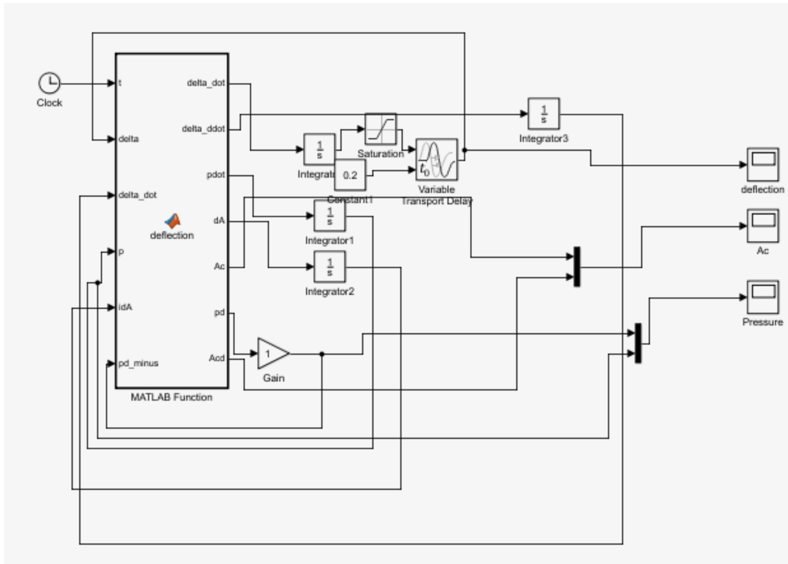


Figure 4.5: Simulink model with time delay

4.2.3 Adding Noise

As mentioned in section 4.1, the noise here was modeled as white noise. Here in the Simulink Model, the noise was added as a band-limited white noise block to the deflection. With this block, the level of noise can be adjusted by changing the power value of the block. Figure 4.6 shows the model configuration with noise.

4.3 Conclusion

This chapter first analyzed the time delay and noise in the system in details. Then, the process of adding time delay and noise to the Simulink model was explained. In the next chapter, the use of the Simulink model to

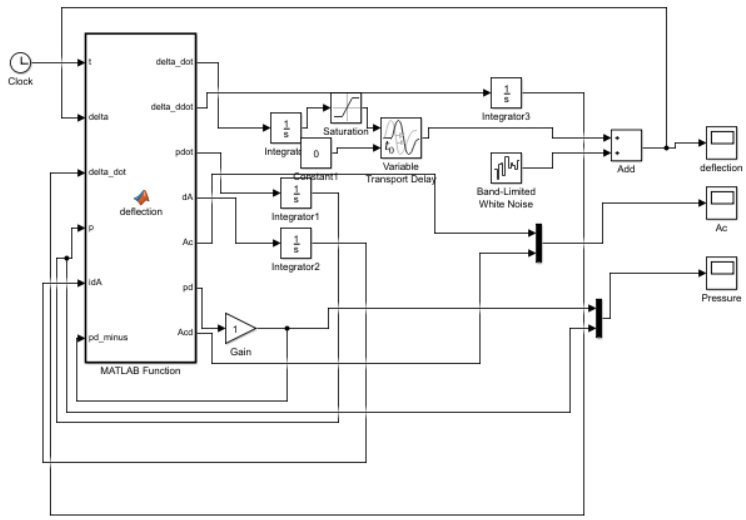


Figure 4.6: Simulink model with noise

do conduct tests about how both time delay and noise affect the system is discussed.

Chapter 5

Simulation Results Considering the Influence of the Sensor

From Chapter 4, a simulation with the influence of the sensor, namely, due to time delay and noise, was built in Simulink. In this chapter, we will use the model to evaluate the influence of the ultrasonic sensor on the ability to control tire-surface contact area.

For evaluation purposes, test 1 from Chapter 3 will be repeated; i.e., the test with a sudden change in demand of contact area. Section 5.1 examines the effect of time delay and how the K_P and K_I control gains were adjusted to minimize the influence, while section 5.2 describes the influence of noise on the system and the maximum level of noise the system can endure.

5.1 Test about the Time Delay

As discussed in Chapter 4, a 0.2-second time delay was added in the simulation, mainly based on the fact that deflection is calculated after the wheel turns a full round.

The delay caused the system response to vary widely at first, so that a saturation block was used at the deflection port. This does not solve the problem but it does keep the simulation running to enable diagnostics and tuning. In order to make the control sequence work normally, it was necessary to adjust the K_P and K_I gains in the PI controller.

When the gains were set to $K_P = 50$ and $K_I = 0.2$, respectively, the simulation yielded the results in Figure 5.1. This is evident, since compared to the simulation results without time delay, the gains used here were much smaller. High values of K_P and K_I will cause more oscillation in the system response, or even make the system unstable. Meanwhile, with smaller K_P and K_I, the response of the system is generally slower.

Since the 0.2-second time delay here is just a reference at 80km/h, actual time delay may vary. Therefore, a gain-scheduling PID control will likely be necessary.

A major difference can be found if we compare the pressure plots of the two cases. In the case without time delay, the desired pressure p_d went much higher (or lower, depending on whether it is an inflation or deflation process) than the pressure at equilibrium. This drove the system to run fast. However, because of the delay in measuring vertical deflection, we can not make the p_d too far from the current pressure. For most of the time, the actual tire pressure was closely following the desired pressure.

With the new K_P and K_I, the rise time for the initial step response is still acceptable for both inflation and deflation process, with almost no overshoot. However, if the actual contact area did not reach the ideal contact

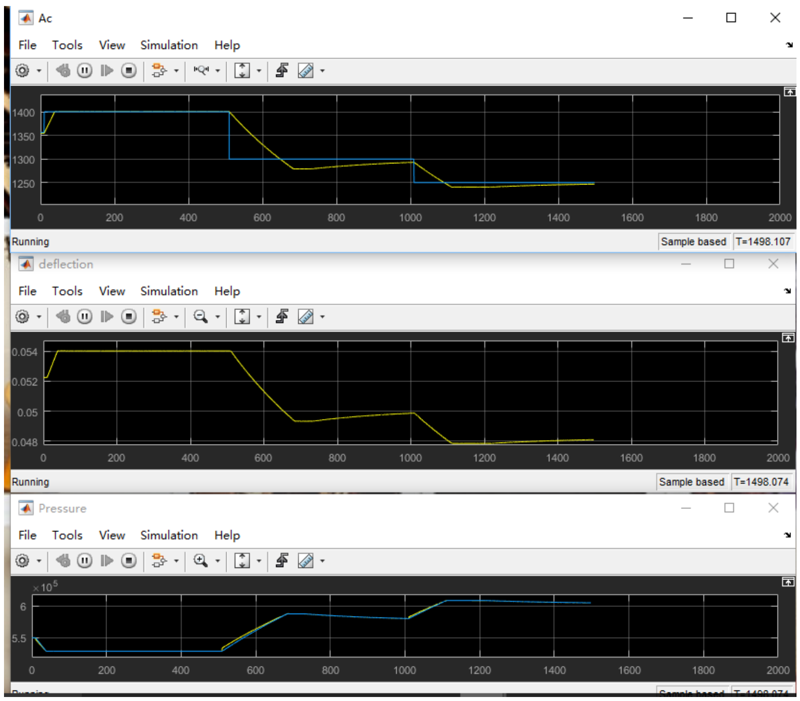


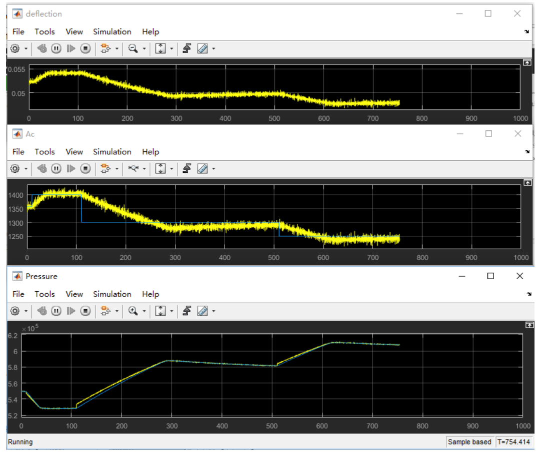
Figure 5.1: Results with Time Delay

area for a period of time, there was a delay for the next movement. This is due to the integration of error in contact area, and can be solved by resetting (unwinding) the integral error.

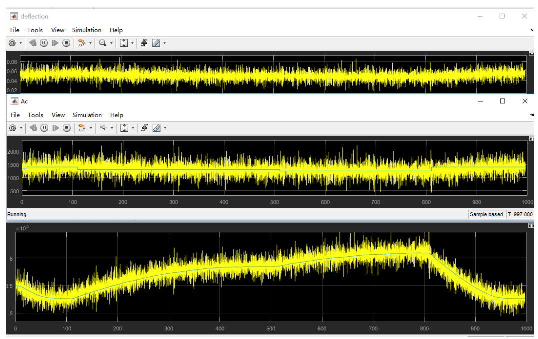
5.2 Test about the Noise

In the noise test, the idea was to figure out the limitation of noise level under which the simulation can still yield reasonable results; i.e., the system will still start inflating the tire if the desired contact area is smaller than the current contact area and vise versa. The noise level was represented by variance, σ_n^2.

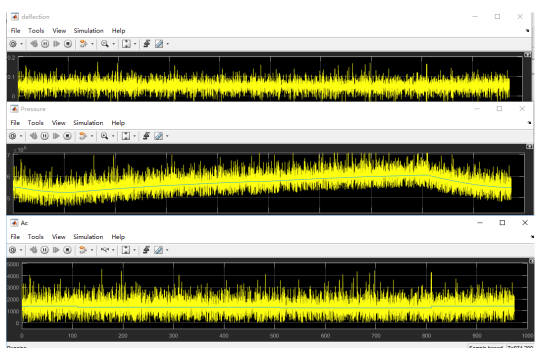
Figure 5.2 shows the results for noise power level $\sigma_n^2 = 1 \times 10^{-8}$ m^2, $\sigma_n^2 = 1 \times 10^{-5}$ m^2, and $\sigma_n^2 = 1 \times 10^{-4}$ m^2 in the measurement of vertical deflection. From the $\sigma_n^2 = 1 \times 10^{-8}$ m^2 plot, we can see that the system can operate well with small noise. Both the change in the contact area and the change in pressure can be clearly seen. When noise level reaches $\sigma_n^2 = 1 \times 10^{-5}$ m^2, the change of the simulated contact area and deflection are overshadowed by the noise; however, the pressure plot is still showing the right trend. Finally, when the noise level reaches 1×10^{-4} m^2, the platform in the pressure plot where tire pressure was supposed to stay the same value completely disappeared, which means the system is inflating when it is supposed to be off. Considering the most simple case where we are only trying to do an on-off control for the CTIS, the system can still be recognized as effective, as long as the trend in pressure is correct. Therefore, if the noise from the sensor is larger than



(a) $\sigma_n^2 = 1e - 8m^2$



(b) $\sigma_n^2 = 1e - 5m^2$



(c) $\sigma_n^2 = 1e - 4m^2$

Figure 5.2: Results of Noise Test

1×10^{-4} m^2, on average, the system is no longer effective.

Another fact here is that in cases with noise, when the system starts inflating, there is a rapid rise in pressure at the beginning of the inflation process. This may be due to the effect of noise and the change in demand, but the exact reason remains unknown, and it is actually shortening the inflation process.

5.3 Conclusion

This chapter reviewed results in simulating the controlled with wit the influence of time delay and noise. The influence of the time delay was minimized by adjusting the proportional and integral gain in the controller. A maximum noise level that the system can endure was also determined.

Chapter 6

Discussion

This chapter provides some insight into the problems with the simulation that were not covered in Chapter 2 to Chapter 5. These problems are mainly concerned with the links and differences between the simulation and the actual CTIS system, especially as regards any deficiencies in the model. The discussion in this chapter will also pave way to the conclusions in Chapter 7. This chapter also describes directions of some possible extensions of the research.

6.1 Deficiencies of the Model

Like all model simulations, there are some deficiencies in this case. In this section, the deficiencies will be explained, along with some possible solutions.

6.1.1 Simplification of the Inflation Model

As introduced in Chapter 2, the tire inflation process was simplified as a simple first order system. This simplification is reasonable in that it correctly reflects the trend between tire inflation pressure and the (supply) flow rate.

Moreover, the inflation model is not a key point here and it is reasonable to simplify this process to speed up the modeling process and simulation. However, if we want to do some quantitative analysis regarding to the nature of the inflation process, this model is far from adequate. The main problems with the current model are:

1. The simulated inflation time is shorter than the actual inflation time.

   In the simulation, the inflation time is much shorter than the actual inflation time of the tire. This may cause problems in choosing parameters while building the actual controller.

2. The difference between inflation and deflation process.

   In the simulation, the same model was used for inflation and deflation process. However, the two processes should be modeled differently if we want to build a more accurate model. The deflation process should be modeled with an effort source; i.e., environmental air pressure drives (passive) deflation, while the inflation process is driven by an active flow source; i.e., air flow of the pump. In this case, deflection could take longer than indicated, and this would slow the process further.

In an actual development project, this could be solved by simply taking measurements of the inflation and deflation process of an actual tire, and use the data to identify more accurate model parameters. So far there are few studies on this, probably because the inflation and deflation processes are often ignored in other studies. Researchers are often more interested in measuring the characteristics of the tire under designated pressure, while the actual dynamic process of inflating or deflating a tire is more like preparation work. However, if we want to build a real-time inflation system, the accurate modeling of the inflation process is probably necessary.

6.1.2 The Algorithm to Get Tire Deflection

The algorithm to get the maximum deflection from the cycle was not included in the simulation. In the actual system, the vertical deflection comes from finding the minimum distance from the ultrasonic sensor when the wheel completes a rotation, which requires wheel speed signal and possibly a trigger signal to mark the start and end of a rotation. However, in the simulation, the deflection was simply calculated based on previous states. Therefore, in the simulation, we were not calculating vertical deflection from the 'U'-shaped signal, like the ones seen in Magori's [18] and Tuononen's [16] reported works.

As a matter of fact, it is not economical to build the input signal with this algorithm. If we have to add the actual deflection calculation process in the simulation, we have to generate a U-shaped signal based on calculated deflection and wheel speed signal, and then try to find the maximum deflection in one cycle. Since both steps are based on the same given wheel speed, the deflection would probably be the same.

Moreover, since the changing of tire deflection is very slow compared to the sampling frequency; i.e., the frequency of wheel spinning in this case, it is still reasonable to simulate the performance of the system without adding the algorithm to get the deflection. Even considering the cases with noise, it would not cause much difference since we only consider noise level in variance here. However, this algorithm may increase the time delay in the sensing process. Therefore, actual time delay may be larger than the value used in the simulation. Detailed time delay can not be estimated until actual measurements are made.

6.2 Some possible Extensions of the Study

This section provides some ideas to elaborate the simulation as well as some possible improvements of the real system.

6.2.1 Possible Improvements of the Simulation

In chapter 1, we discussed the general assumptions in the model and simulation. Under these assumptions, the simulation is actually quite limited. To make the simulation more realistic, we should consider the cases under different assumptions, namely:

1. Considering the case of soft terrain.

   The simulation was done assuming hard terrain where the deformation of the terrain is not considered. Nonetheless, the original objection of the system is to solve off-road problems. Therefore, if we want to go further into this problem, we need to consider the case of soft terrain and include the road-tire reaction in this problem.

2. Using a more realistic estimation of the contact area.

   In the simulation, the contact area was calculated with equations given by Upadhyaya and Wulfsohn [17]. These equations assume elliptical contact area and include an experimental coefficient. Although the experimental coefficient was adjusted according to measured data provided by Stallman [11],the output is still not perfect. Another method may be trying to simulate the contact area using finite element analysis results. This was proved effective by Nakajima.(add citation) If a more detailed tire model was built, more analyses can be done relating vehicle dynamics, including speeding, steering, and stability of the vehicle.

6.2.2 Possible Improvements of the Sensing System

The major problem in the real sensing system now is the noise. However, from Chapter 5, the simulated results show that the control system is actually somewhat robust to the influence of noise. Even when the changes in contact area and deflection can not be seen explicitly because of too much noise, the system was still able to generate a control action for the pressure to go up or go down, assuming that the noise is an ideal zero-mean white noise.

In order to improve the performance of the real system, we may need to introduce an algorithm to provide a better estimation for the states under the influence of more realistic and complicated noise. The use of a Kalman filter, for example, could be evaluated with signals measured from the real system.

Another option is to adopt other sensors with less noise. If the actual major source of noise is the reflection from wires in the tire tread, it may be necessary to change to other types of sensors. Tuononen [16] has provided a series of different sensor options to measure tire deflection.

6.2.3 Additional Functions to Improve the System

While building the simulation, some new ideas of how the control process can be improved merged. Some additional functions are required to achieve better performance of the control system.

As mentioned in chapter 3, the contact area commands in the simulation were just arbitrary inputs. It was considered that the driver could switch the 'inflation modes' based on different types of terrain. However, to maximize the effect of the control system, a better solution may be trying to detect the type of terrain automatically, which could be done by measuring slip rate or tire sinkage. This requires an additional algorithm that figures out the type of terrain based on measured slip rate or tire sinkage in real time. More measurements of the tire on different types of terrains is needed here.

Another function is to optimize the K_P and K_I gains based on different levels of time delay. According to chapter 4, the 0.2-second time delay is estimated at a vehicle speed of 80 km/h. At lower vehicle speed, the best gains for the system may vary. In this way, if we can get the best K_P and K_I for different levels of time delay, it would probably improve the performance of the control system, especially for lower vehicle speeds.

6.3 Conclusion

This chapter discussed problems both in the simulation and in an actual tire contact area sensing and control system. It also offers some directions for further studies on this problem.

Chapter 7

Conclusion

A simulation was built in order to evaluate the idea that tire-surface contact area can be controlled by inflating or deflating the tire. In a proposed system, tire contact area is estimated based on measuring tire vertical deflection. This study is limited to the case where the tire interacts with hard terrain, allowing assumption of an elliptical contact area based on measured tire deflection. This is only necessary to allow formulation of a complete system model.

A few tests were conducted using a simulation to estimate the performance of the system under different driving scenarios, namely simulated changes in terrain stiffness, changes in vertical applied load, and pressure changes in the tire caused by the change in temperature. It turns out that the system is able to control contact area according to demands and make up for small or slow changes of tire pressure. Since the inflating and deflating processes are slow, the reaction time of the system is quite long; also, the system can not make up for sudden changes to the driving condition like tire burst.

On proving the validity of the control system, the influences of the sensor, noise and time delay, was added to the simulation. The influence of time delay can be minimized by changing the parameters in the controller. The noise limit for the control system was also evaluated.

The model of the tire in the simulation was not perfect. If we want a more accurate simulation of the system performance, a more realistic model of the tire is required, as well as more detailed tire-road interaction models. However, this simulation did prove the validity of the concept, and meanwhile provided some insights for research and development of the actual system. Finally, the results from this study suggest:

1. The tire inflation model can be improved by using a more realistic model.

2. The model should be extended to more directly account for operation of a tire on soft.

3. In order to improve the performance of the real system, we need to lower the noise effects by adding a Kalman filter or using other types of sensors.

Appendices

Appendix A

Codes for Obtaining K_p and K_s

```
% The University of Texas at Austin
% Mechanical Engineering Department
% Da Fang
% Cooper.m
clear
close all
global Kp Ks
v_displacement=(0:10:80)'/1000;%m
pressure=[100 300 550];%kPa
v_load=[0 0 0
    1905 3469 6354
    4716 9445 15537
    7221 15559 25250
    9947 21968 36872
    13415 29011 48446
    17673 37581 62502
    21582 45717 74730
    25616 54191 88151];%N
```

```
% figure(1)
% plot(v_displacement,v_load(:,1),v_displacement,v_load(:,2),...
% ...v_displacement,v_load(:,3));
% xlabel('deflection/m'),ylabel('load/N')
% legend ([num2str(pressure(1)),'kPa'],...
% ...[num2str(pressure(2)),'kPa'],[num2str(pressure(3)),'kPa'])
%
for i=1:3
k(i,:)=polyfit(v_displacement,v_load(:,i),1);
end
%
% figure(2)
% plot(pressure,k(:,1),'or')
% hold on
% plot(pressure,k(:,1))

K=polyfit(pressure',k(:,1),1);

Kp=K(1);
Ks=K(2);
```

Appendix B

Codes of the Simulation

B.1 Main

```
% The Universtiy of Texas at Austin

% Mechanical Engineering Department

% Da Fang

% main.m


clear

clc

close all

%

global F b Kp Ks m_t pd  tau pmax pmin t_end K count pd_range d R2 w on_off Ac Ac

F=58900;

%F=9.8*6595;%N

b=6580.2;%NMm/s

p0=550000;%Initial inflation pressure/Pa

m_t=240;%kg

d=1341.4;%mm

R2=(d-406.4)/2;%0;%mm
```

```
w=379.5;%mm tread width
count=0;%initialize

Kp_a=800;
Ki_a=10;

%pd=300000;%Pa % desired pressure can be specified for testing

pd_range=100;
%initializing CTIS
t_end=0;
on_off=0;

Kp=1.78085819672131;%N/(m*Pa)
Ks=148113.237704918;%N/m

K=143;%parameter for evaluating time in Schultz

pmax=760000;%Inflation pressure/Pa
pmin=100000;%Deflation pressure/Pa
tau=600;%time constant/s
tf=2000;
dt=0.02;
```

```
delta0=0.05228;%m

Ac=1356;%initializing the contact area for the controller

Acd=1356;%initializing

pd=p0;%initialzing

idA0=0;%initialzing integration

deltadot0=0;

x0=[delta0;deltadot0;p0;idA0];

tspan=[0 tf];

N=floor(tf/dt);

%[t,x] = ode45(@deflection,tspan,x0);

%[t,x] = ode23(@deflection,tspan,x0);

[t,x] = rk4fixed('deflection',tspan,x0,N);


N = length(t);

for i=1:N

    Y = zeros(1,5);

    [xd Y] = deflection(t(i),x(i,:));

    delta_dot(i)=Y(1);

    open(i)=Y(2);

    k(i)=Y(3);

    Ac_log(i)=Y(4);

    pd_a(i)=Y(5);

    Acd_log(i)=Y(6);
```

```
    F_log(i)=Y(7);
end
figure(1)
subplot(2,1,1)
plot(t,x(:,1)*1000)
title('deflection vs time'),xlabel('time/s'),ylabel('deflection/mm')
subplot(2,1,2)
plot(t,x(:,2)*1000)
title('deltadot vs time'),xlabel('time/s'),ylabel('deltadot/mm*s^-1')
figure(2)
plot(t,x(:,3)/1000,'b',t,pd_a/1000,'r')
legend('actual','desired')
title('pressure vs time'),xlabel('time/s'),ylabel('pressure/kPa')%,...
...axis([0 tf 300 800])

figure(3)
plot(t,Ac_log,'b',t,Acd_log,'r')
legend('actual','desired')
title('Contact Area vs time'),xlabel('time/s'),ylabel('contact area/cm^2')

% figure(4)
% plot(t,F_log/1000)
% title('vertical load'),xlabel('time/s'),ylabel('Load/kN')
```

B.2 System Function

```
% The Universtiy of Texas at Austin

% Mechanical Engineering Department

% Da Fang

% deflection.m


function [xdot,y]=deflection(t,x)


global F b Kp Ks m_t tau pmax pmin count d R2 w pd_range pd ...

...K t_end on_off Ac Acd Kp_a Ki_a ;


delta=x(1);%deflection

delta_dot=x(2);%speed of deflection


p=x(3);%pressure

idA=x(4);


%inflation testing

%pd=300000+10000*floor(t/50);
```

```
%pd=550000-10000*floor(t/50);
%controller
dA=Ac-Acd;

% Acd=1356;

%test 1
Acd=1356;
if t>10 && t<510
    Acd=1400;
end
if t>=510 && t<1010
    Acd=1300;
end
if t>=1010 && t<1510
    Acd=1250;
end
if t>=1510
    Acd=1400;
end

% %test 2
% if t<=10
```

```
% F=58900;
% end
%
% %slow
% if t>10 && t<510
%     F=0.002*(t-10)*(1/3)*58900+58900;
% end
%
% %quick
% if t>10 && t<20
%     F=0.1*(t-10)*(1/3)*58900+58900;
% end


%%%% Schultz:
on_off0=on_off;
if t>t_end

if p<pd-pd_range
    on_off=1;
    t_open=K*(pd-p)/147000;
    t_end=t+t_open;
else if p>pd+pd_range
```

```
        on_off=-1;
        t_open=K*(p-pd)/147000;
        t_end=t+t_open;
    else
    t_open=0;
    on_off=0;
    t_end=t;
    end
end

if on_off==on_off0
        count=count+1;
else
    if count<4
            K=K-0.2;
            else if count<5
                K=K-0.1;
                else if count<=7
                    else if count<9
                    K=K+0.1;
                    else K=K+0.2;
                    end
                end
```

```
            end
        end
        count=0;
end
end
%%%

k=p*Kp+Ks;

delta_ddot=(F-k*delta-b*delta_dot)/m_t;

if on_off==1
pdot=(pmax-p)/tau;
%
% %test 3
% pdot=(pmax-p)/tau+(80/313)*p/3600;
else if on_off==-1
        pdot=(pmin-p)/tau;
        %pdot=(pmin-p)/tau+(80/313)*p/3600;
    else pdot=0;
        %pdot=(80/313)*p/3600;
    end
end
```

```
lc=2*sqrt(delta*100*d/10);
lw=0.737*2*2^0.5*sqrt(delta*100*R2/10);

    Ac=(pi)*lc*lw/4;%cm^2
if lw>w
    lw=w;
    a=w/lw;
    eta=sqrt(2*(1-a))^0.5-a*(1-a^2)^0.5;
    Ac=(pi-2*eta)*lc*lw/4;%cm^2
end

pd=p+Kp_a*dA+Ki_a*idA;

xdot=[delta_dot;delta_ddot;pdot;dA];

y(1)=delta_dot;
y(2)=on_off;
y(3)=k;%stiffness
y(4)=Ac;
y(5)=pd;
y(6)=Acd;
y(7)= F;
```

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